A PERFORMANCE AND COST EVALUATION OF EG&G'S BIOCUBE™ AEROBIC BIOFILTRATION SYSTEM FOR THE DESTRUCTION OF HYDROCARBON VAPORS FROM FUEL-CONTAMINATED SOILS

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A PERFORMANCE AND COST EVALUATION OF EG&G'S BIOCUBE™ AEROBIC BIOFILTRATION SYSTEM FOR THE DESTRUCTION OF HYDROCARBON VAPORS FROM FUEL-CONTAMINATED SOILS

by

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SECTION 1

INTRODUCTION

This document provides a performance and cost analysis for an aerobic biofiltration treatment system used to treat extracted petroleum hydrocarbon vapor from contaminated, unsaturated (vadose zone) soils. The Biocube™ Aerobic Biofiltration System manufactured by EG&G's Rotron Division in Saugerties, New York was evaluated by Parsons Engineering Science, Inc. (Parsons ES) at the Patrick Air Force Base (AFB), Florida, Base Exchange (BX) Service Station from 15 January through 26 February 1994. The system was evaluated in conjunction with an ongoing bioventing pilot test directed and funded by the Air Force Center for Environmental Excellence (AFCEE), Technology Transfer Division (ERT). The purpose of this test was to independently measure both the performance and the cost effectiveness of the Biocube™ system.

A pilot test work plan was developed for testing and evaluating the EG&G Biocube™ Aerobic Biofiltration System at Patrick AFB. The primary objectives of the evaluation were:

1) To determine the effectiveness of the Biocube™ system at reducing concentrations of volatile organic compounds (VOCs) in vapors extracted from the soil prior to release of the vapors into the atmosphere;

2) Determine the reliability and maintainability of the Biocube™ system; and

3) Estimate the cost of installing and operating the Biocube™.

Secondary objectives included improving the sampling, analysis, and air flow adjustment process to achieve a more rapid Biocube™ system stabilization; and achieving removal rates of volatile hydrocarbons of greater than 90 percent for benzene, toluene, ethylbenzene, and xylenes (BTEX) and 75 percent for total volatile hydrocarbons (TVH) at a process-stream vapor flow rate of 50 standard cubic feet per minute (scfm) or less.

The evaluation of this system at the Patrick AFB BX service station site was disappointing. The system did not perform as advertised, and volatile hydrocarbon removal efficiencies fell far short of test objectives. The following sections describe the test conditions and results of the performance and cost evaluation.

SECTION 2

DESCRIPTION OF TECHNOLOGY

2.1 BIOLOGICAL TREATMENT OF ORGANIC VAPORS USING VAPOR EXTRACTION

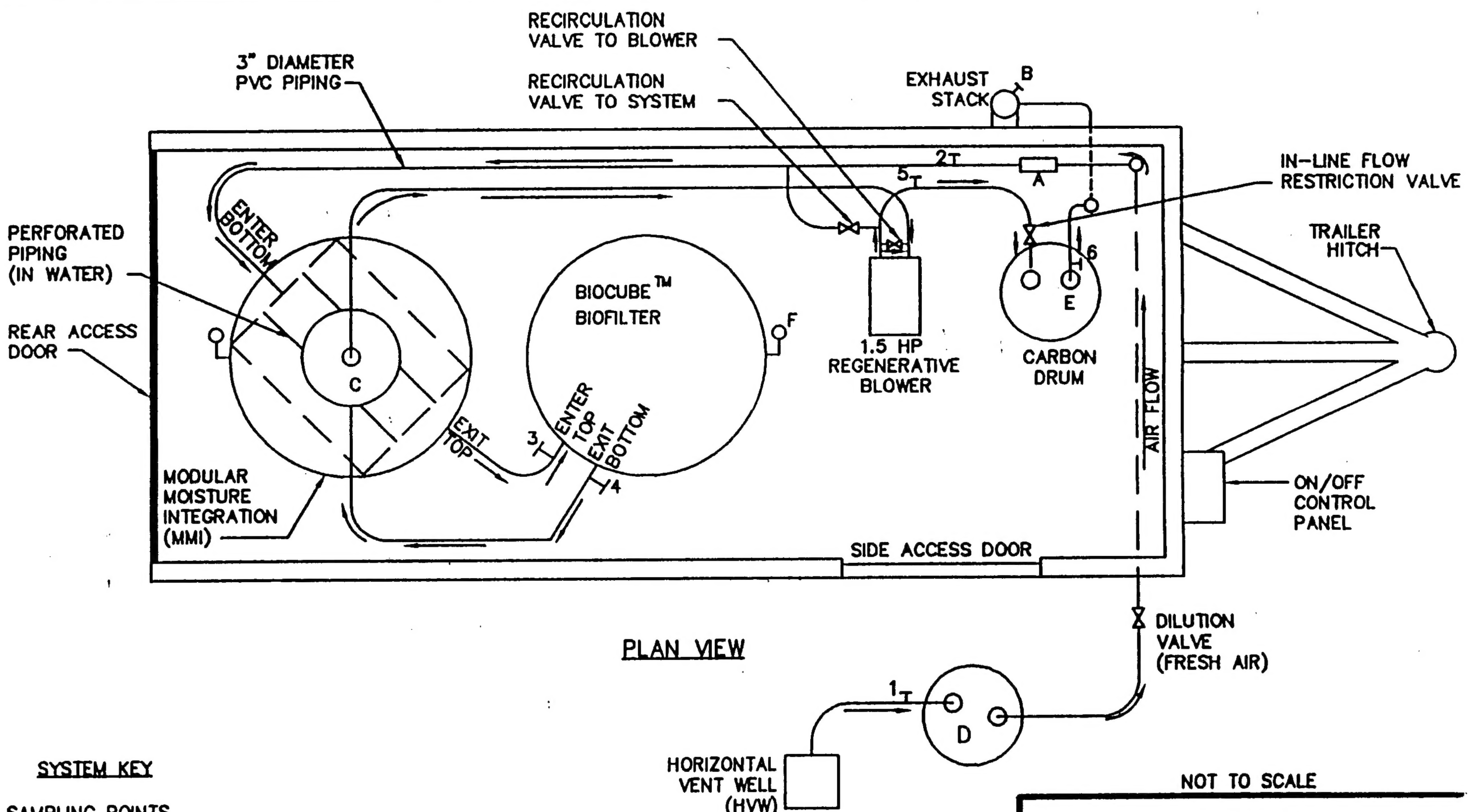
The Biocube™ technology is an aboveground biofiltration unit designed and marketed by EG&G Rotron Division of Saugerties, New York. As hydrocarbon-contaminated vapors pass through a filter bed, the organic fuel constituents are removed via adsorption and biodegradation. The process is dependent on the bioavailability of hydrocarbons supplied to the naturally occurring microbes distributed within a bed of porous material onto which the gaseous contaminants are adsorbed. The hydrocarbon-degrading microbes require a controlled temperature and moisture environment to perform efficiently.

2.2 PROCESS DESCRIPTION

The Biocube™ system was housed within a mobile trailer with external trailer dimensions measuring 24 feet long; 8 feet wide; and 11.5 feet high, and a gross vehicle weight rating (GVWR) of 11,200 pounds.

A schematic of the Biocube™ unit is shown in Figure 2.1. The Biocube™ includes its own vacuum blower which extracts soil vapors from the bioventing well and through a condensate (moisture) knockout drum to prevent water from accumulating in the intake hose. An influent soil gas sampling point 1 was installed in line before the knockout drum to monitor the vapor concentrations from the vent well prior to any dilution. Following the condensate knockout drum, an inline fresh air dilution valve installed outside the trailer was used to maintain a constant influent contaminant concentration of approximately 1,000 parts per million, volume per volume (ppmv) TVH. Following the fresh air dilution valve the influent vapor pipeline enters the trailer through the floor, where the flow rate is measured at an inline flow meter. Following the flow meter, influent sampling point 2 was installed to measure the vapor concentrations after dilution (Figure 2.1). The vapor stream next enters a modular moisture integrator (MMI) where the air stream was humidified. According to EG&G, the MMI ensures high humidity in the vapor stream entering the biofilter.

Following the MMI, the vapors enter the top of the biofilter. The filter medium consists of a proprietary mixture of inorganic and organic substrate containing active hydrocarbon-degrading bacteria. Sampling point 3 was installed to check vapor concentrations between the MMI and the biofilter. Because the influent vapors pass through a water bath in the MMI, a potential solubilization of BTEX could occur in the



NOT TO SCALE

<u>SYSTEM KEY</u>

SAMPLING POINTS

1 INFLUENT SOIL GAS FROM HVW (PREDILUTION)
2 INFLUENT SOIL GAS TO MMI (POSTDILUTION)
3 INFLUENT SOIL GAS TO BIOFILTER (POST MMI)
4 EFFLUENT SOIL GAS FROM BIOFILTER (BEFORE BLOWER)
5 EFFLUENT SOIL GAS AFTER BLOWER AND BEFORE CARBON
6 EFFLUENT FROM CARBON

OTHER

A INFLUENT FLOW MEASURING POINT
B EFFLUENT FLOW MEASURING POINT
C EG&G CYCLONIC MOISTURE SEPARATOR DRUM (55 GAL.); PLACED ON TOP OF MMI
D ES INSTALLED CONDENSATE KNOCKOUT DRUM (55 GAL.)
E 55 GAL. VAPOR-PHASE CARBON DRUM (200LB)
F TEMPERATURE GAUGE (3-BIOFILTER, 1-MMI)

FIGURE 2.1

BIOCUBE™ PIPING SYSTEM AI SAMPLING POINT SCHEMATIC

BIOCUBE™ PERFORMANCE AND COST EVALUATION
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water prior to entering the biofilter. Following sampling point 3, the vapor stream passes through the biofilter medium, exiting through the bottom of the biofilter where effluent sampling point 4 was installed to measure the actual TVH reduction occurring within the biofilter media. Following sampling point 4, the treated vapors enter another condensate knockout drum (EG&G cyclonic moisture separator) positioned on top of the MMI. The air stream exits the moisture separator and flows to the blower. The air stream is pulled through the blower (under vacuum) then exhausted.

A recirculation loop was installed at the blower between the intake and exhaust lines to allow multiple passes through the biofilter and to control the effluent discharge rate to the atmosphere. Sampling point 5 was installed to monitor the treated biofilter effluent vapor concentrations (Figure 2.1). Following sampling point 5, the air stream flows through a 55-gallon vapor-phase carbon drum used to ensure the 99-percent TVH removal required by the State of Florida. Sampling point 6 was installed to check final system effluent concentrations and to monitor for hydrocarbon breakthrough downstream of the carbon drum. Following sampling point 6, the air stream is vented through the exhaust stack where an effluent flow measurement port was installed to check the mass balance of the system air flow.

2.3 VENDOR'S STATEMENT OF SYSTEM CAPABILITIES

According to EG&G Rotron, the mobile Biocube™ system provided for this test was not considered a prototype, but a fully capable and tested system. EG&G provided information to AFCEE and Parsons ES indicating that removal efficiencies of greater than 90 percent for the BTEX compounds could be expected. In addition to BTEX removal, EG&G also claimed that a 75-percent removal efficiency for TVH at a flow of 50 scfm was achievable. Actual removal efficiencies achieved at the Patrick AFB test site were significantly less, as discussed in Section 3.

2.4 SPECIAL CONSIDERATIONS/LIMITATIONS

Site-specific conditions can limit the application and performance of an aerobic biofilter system. Specific limitations pertaining to the EG&G Biocube™ Aerobic Biofiltration System are listed below:

- System acclimatization - the initial period during which temperature, humidity, and process air stream (extracted soil gas) are introduced to the microbes within the biofilter medium. This process may continue for several weeks before the microbes begin to show significant removal efficiency.

- During the acclimatization period, biofilter influent hydrocarbon concentrations in the extracted soil gas should be approximately 1,000 ppmv TVH according to EG&G Rotron. At sites where TVH concentrations are >1,000 ppmv in the extracted soil gas, it is necessary to dilute the vapors with fresh air to achieve approximately 1,000 ppmv TVH prior to introduction into the biofilter media. According to EG&G, higher TVH values could create toxic conditions for the microbes, thereby limiting the hydrocarbon vapor destruction efficiency.

- External water and power support requirements are necessary for system operation. A potable water source capable of supplying 2 gallons per hour at 20 to 100 pounds per square inch (psi), and electrical power service of 60 hertz, 220 volts, and, 30 amps also is required.

- Disposal of BTEX-contaminated water from the MMI is required. The exact quantity of water was not determined by this test, however based on the capacity of the MMI, it is anticipated that a minimum of 175 gallons would require disposal upon project completion.

2.5 REGULATORY ACCEPTANCE

Based on information provided by EG&G Rotron, no list of regulatory approvals or list of permitted facilities has been compiled to date. A knowledge of the local regulatory permitting requirements for vapor extraction treatment systems would be required prior to considering this technology. No umbrella permits are available to allow operation of Biocube™ systems.

SECTION 3

FIELD DEMONSTRATION RESULTS

3.1 SITE DESCRIPTION

An evaluation of the Biocube™ Aerobic Biofiltration System was conducted between 15 January and 26 February 1994, at Patrick AFB, Florida at the active BX Service Station.

The BX Service Station site is part of an ongoing bioventing pilot test study. Soil and groundwater contamination from previous unleaded gasoline leaks from underground storage tanks (USTs) has been identified at the site. A soil gas survey was initially conducted to verify site conditions, and to verify that sufficient soil contamination existed to warrant conducting the bioventing pilot test. The initial soil gas sample laboratory results ranged from 38,000 to 100,000 ppmv for TVH within the study area (Parsons ES, 1993).

The average water table depth is approximately 5 feet below ground surface (bgs). A horizontal vent well (HVW) was installed at 4 feet bgs as part of the bioventing pilot test. The HVW was placed in the center of the highest TVH readings obtained during the initial soil gas survey at the site. The HVW was constructed of 4-inch, Schedule 40 polyvinyl chloride (PVC) pipe with 30 feet of 0.03-inch slotted well screen. The entire length of screened interval was placed within the contaminated soil interval. The entire study area at this site is paved, which significantly minimizes the potential for short-circuiting and increases the area of influence for air injection or soil vapor extraction through the HVW.

Because initial soil vapor concentrations at this site were high, bioventing through the use of air injection was ruled out due to the potential for vapor migration. Soil vapor extraction was required to reduce soil vapor concentrations before the system could be converted to a more standard air injection bioventing system. Initial high soil vapor concentrations were reduced through soil vapor extraction utilizing an internal combustion engine (ICE) vapor extraction system manufactured by VR Systems Inc. of Anaheim, California. During a 3-month ICE unit performance evaluation conducted at this site, initial TVH concentrations of 47,000 ppmv in extracted soil gas were reduced to approximately 2,400 ppmv. Following the VR Systems test, AFCEE requested that the Biocube™ vapor extraction system manufactured by EG&G Rotron be used to treat the remaining soil gas vapors and that Parsons ES provide an independent evaluation of its performance and cost of operation.

3.2 REGULATORY APPROVAL/REQUIREMENTS

Florida Department of Environmental Protection (FDEP) policy states that all vacuum extraction units must use a catalytic or thermal oxidation device, or its equivalent, to reduce VOC emissions by at least 99 percent during the first 2 months of operation. After 2 months of operation, the reduced untreated effluent concentrations are evaluated with the SCREEN air modeling program. If the results show that the emissions are below acceptable ambient air standards at the area of greatest impact, the air emissions controls may be discontinued after concurrence from the FDEP. The objective of the test conducted at the Patrick AFB BX Service Station was to use the Biocube™ to remove additional BTEX and TVH vapors, and to achieve 99-percent VOC removal through the use of activated carbon polishing of the biofilter effluent.

3.3 TEST CONDITIONS

Based upon manufacturer specifications, the flow capacity of the Biocube™ is 0 to 50 scfm. This flow range established by the manufacturer was based on a TVH influent concentration of approximately 1,000 ppmv. The EG&G test objectives were to achieve removal efficiencies of 90 percent for BTEX and 75 percent for TVH based on an influent concentration of 1,000 ppmv TVH. Flow rates between 3 and 50 scfm were tested to determine the optimum flow rate for maximum TVH reduction.

The initial soil gas TVH concentration was approximately 2,400 ppmv. Therefore a dilution valve was used to reduce the Biocube™ influent concentration to approximately 1,000 ppmv TVH. Continual adjustments of the dilution valve were necessary to maintain a 1,000-ppmv TVH influent concentration.

During the entire test evaluation, 55-gallon (200-pound) drums of vapor phase carbon were installed after the Biocube™ system to remove the residual soil gas VOC concentrations to meet the FDEP VOC emission standard for vapor extraction systems. A total of three carbon drums were used during the test.

3.4 OBSERVED PERFORMANCE

The Biocube™ began the acclimatization phase for water (moisture) and temperature on 16 January 1994, and began receiving extracted soil gas vapor from the HVW on 21 January 1994. Following the initial 8 days of operation, at approximately 1,000 ppmv TVH and flow rate of 30 scfm, no measurable differences (<10 percent) between Biocube™ influent and effluent TVH and BTEX concentrations were detected based on laboratory analytical results using US Environmental Protection Agency (EPA) Method TO-3.

At the end of the initial 8 days of operation, EG&G reconfigured the Biocube™ piping system to permit recirculation of a greater percentage of the effluent air stream. A schematic of the reconfigured Biocube™ piping system and the various sampling points are shown in Figure 2.1.

Portable, hand-held instruments capable of measuring percent oxygen and TVH were used frequently throughout the test period to monitor the Biocube's™ removal efficiency. In addition to continual on-site monitoring, laboratory samples were

collected weekly from the influent and effluent sampling points (2 and 5, respectively) and analyzed for TVH and BTEX using EPA Method TO-3 to confirm actual removal efficiency. Table 3.1 illustrates the Biocube™ removal efficiencies for BTEX and TVH at various loading rates that occurred during the test period. C_1 through C_5 volatiles comprised from 4.9 to 13 percent of the TVH, and EG&G acknowledged that C_1 through C_5 hydrocarbons were not effectively removed by the Biocube™ process.

Maximum removal efficiencies of 90.8 percent for BTEX and 29.5 percent for TVH were achieved at very low (and impractical) loading rates of 0.08 grams of BTEX per day per cubic foot of biofilter (g/d/ft^3) and 3.8 g/d/ft^3 of TVH.

3.5 LIMITATIONS EXPERIENCED

- System acclimation was not rapidly achieved in this test. In states such as Florida, where a VOC destruction efficiency of >99 percent is required during the first 2 months of a vapor extraction system operation, a backup treatment system must be in place during acclimation. During the Biocube™ demonstration, granular activated carbon (GAC) was used to treat the effluent from the Biocube™ system.

- Vacuum leaks and dilution of process gas were observed within the Biocube™ system. Because the entire system operated under a vacuum, the potential for vacuum leaks is high. Monitoring for oxygen as well as hydrocarbon concentrations was necessary to ascertain whether a reduction in hydrocarbon concentrations was due to a fresh-air vacuum leak or to actual biological degradation. Monitoring for oxygen as well as hydrocarbon concentrations within the influent and effluent vapor stream was conducted at the Patrick AFB site. The oxygen detected in the effluent sample was greater than the influent oxygen content; therefore, it was determined that a vacuum leak was occurring within the system. The reduction in the TVH concentration between influent and effluent samples was adjusted for the dilution to reflect actual removal efficiencies. System leaks were also calculated based upon a flow rate comparison between influent and effluent air streams before and after the Biocube™ system. Dilution occurring from vacuum leaks ranged from 0 to 25 percent during the Biocube™ evaluation. Removal efficiencies shown in Table 3.1 have been corrected for dilution. Attempts were made to reduce the vacuum leaks by using a silicone caulking sealant at all pipe joints and fittings where potential leaks could occur.

- Flow measuring devices installed by EG&G did not provide accurate flow measurements or mass balances. Parsons ES installed additional air flow ports on the influent and effluent piping so that a Dwyer® thermal anemometer could be used to check flow rates and system mass balance calculations.

TABLE 3.1

BIOCUBE™ REMOVAL EFFICIENCIES FOR BTEX AND TVH BASED ON LOADING RATE IN GRAMS/DAY/CUBIC FOOT OF FILTER MEDIUM ($g/d/ft^3$)

Days of Operation	Influent Flow Rate in scfm[c]	Influent Total BTEX ppmv[a]	BTEX Loading Rate in $g/d/ft^3$	BTEX Removal Percentage[d]	Influent TVH ppmv[a/b]	TVH Loading Rate in $g/d/ft^3$	TVH Removal Percentage[d]
3 (1/21/94)	30	24	1.45	0.0	969	55.2	0.0
10 (1/28/94)	9.4	16	0.30	22.5	684	12.2	8.3
20 (2/7/94)	3.2	12	0.08	90.8	433	2.7	23.2
24 (2/11/94)	3.2	14	0.09	72.2	627	3.8	29.5
37 (2/24/94)	49	26	2.53	39.8	1254	116.7	18.2

a/ = Influent concentration based on laboratory analysis using EPA Method TO-3.
b/ = Total volatile hydrocarbons including C1-C5 compounds, which EG&G claimed could not be removed by this system.
c/ = Standard cubic feet per minute calculated using a Dwyer Thermal Anemometer Flow Meter.
d/ = Removal Percentage was corrected for effects of dilution, and represents removal due to the Biocube™ system.

3.6 RELIABILITY

Because the Biocube™ failed to meet initial treatment goals during the test, insufficient data are available to evaluate long-term reliability.

3.7 MAINTAINABILITY

- Because the Biocube™ performed poorly during the initial weeks of the test evaluation, limited data were collected regarding long-term maintenance. During this short-term test, the Biocube™ system required the following monitoring and maintenance:

  - Removal of condensate (moisture) within the inlet vacuum line between the extraction well and the Biocube™ trailer.

  - Daily monitoring of the influent TVH vapor concentrations to prevent excessive influent concentrations to the Biocube™ biofilter, resulting in a less efficient removal process.

  - Maintaining an adequate temperature and moisture content within the biofilter media required daily monitoring during the acclimation phase.

  - Additional treatment and monitoring of the effluent soil gas from the biofilter prior to discharging into the atmosphere in order to meet applicable air emission standards.

  - Monitoring and disposal of BTEX-contaminated water from the MMI.

  - Monitoring for and repair of vacuum leaks throughout the system.

  - Monitoring for condensate/water accumulation throughout the piping system.

Significant startup monitoring is necessary during the acclimation phase (initial weeks) until the system reaches equilibrium. During the initial 32 days of operation at Patrick AFB, the Biocube™ system required a total of approximately 80 hours of onsite monitoring to check flow rates, influent and effluent concentrations, biofilter media temperature, vapor moisture and pressure, and accumulation of water within the piping system.

3.8 COST EVALUATION

During the test of the Biocube™ system, hardware and operating problems precluded establishing consistent, effective system performance under stabilized conditions. The variable operating parameters (e.g., vapor flow rates and influent vapor TVH concentrations), the repairs required to address vacuum leaks, and the reconfiguration of the Biocube™ piping during the test prevented a reliable estimate of operating costs for the Biocube™.

The data shows that costs pertaining to the EG&G Biocube™ may not be applicable because of the poor performance demonstrated by the unit. Based on the best observed removal efficiency of the EG&G unit, approximately 12 Biocube™ units would be required to operate in series to remove 90 percent of TVH in the 49 scfm/1,254 ppmv vapor stream. Since reasonable costs were not derived from the EG&G evaluation, two other biofiltration companies were contacted who claim to have experience with the removal of petroleum hydrocarbons using biofiltration. Based on vendor information only, and not an independent evaluation conducted by the Air Force, an expected range of TVH treatment costs were calculated. Parsons Engineering Science contacted Bohn Biofilter Corporation in Tucson, Arizona[1], and Envirogen Incorporated in Lawrenceville, New Jersey[2].

Vendor Cost Estimates For The Removal Of TVH As Gasoline Vapor Using Biofiltration

Bohn Biofilter Corporation[b/]: (100% Compost - Biofilter)

TVH Influent (PPMV)	Flow Rate (SCFM)	Contact Time (minutes)	Vendor Claimed TVH Removal Percentage	Daily Biofilter Lease +$50 per Day for Sampling/ Monitoring	Additional a/ Carbon Cost to Achieve ≥99%	Estimated Total Daily Cost	Estimated Cost/kg of TVH Removed
		(≈ 400 Ft^3 Biofilter)					
2,000	20 (max.)	20 min.	90	$117	$22.50	$140	$20.94/kg
1,000	20	20	90	$117	$11.10	$128	$38.06/kg
500	20	20	90	$117	$5.55	$123	$73.13/kg
250	20	20	90	$117	$2.70	$120	$142.69/kg

Envirogen, Inc.[c/]: (Proprietary Mix-Biofilter)

TVH Influent (PPMV)	Flow Rate (SCFM)	Contact Time (minutes)	Vendor Claimed TVH Removal Percentage	Daily Biofilter Lease +$50 per Day for Sampling/ Monitoring	Additional a/ Carbon Cost to Achieve ≥99%	Estimated Total Daily Cost	Estimated Cost/kg of TVH Removed
		(≈ 250 Ft^3 Biofilter)					
2,000	40	6	74	$133	$113.00	$246	$18.66/kg
1,000	40	6	81	$133	$41.85	$175	$26.18/kg
500	40	6	85	$133	$16.65	$150	$44.59/kg
250	40	6	87	$133	$7.20	$140	$83.25/kg

a/ Based on an average cost of $33 per kilogram of TVH treated by carbon.

b/ Daily lease based on a $2,000 a month lease plus $1,500 labor for a total $3,500/mo.

c/ Daily lease based on a $2,500 a month lease plus $1,500 labor for a total $4,000/mo.

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1 Point of Contact: Dr. Hinrich Bohn, telephone: 602-624-4644.

2 Point of Contact: Mr. George Skladany, telephone: 609-936-9300.

SECTION 4

SUMMARY

4.1 DESTRUCTION EFFICIENCY

The Biocube™ unit did not achieve the BTEX and TVH destruction efficiencies that were anticipated based on vendor claims. BTEX destruction efficiencies in excess of 70 percent and TVH destruction efficiencies in excess of 20 percent were achieved only when the flow rate and loading to the biofilter were reduced to impractically low levels (3 scfm). BTEX removals of 40 percent and TVH removals of 18 percent were achieved at a more practical 49-scfm flow rate. These destruction efficiencies are much too low for the Biocube™ to be used as the primary vapor treatment technology in states requiring high TVH or BTEX removal efficiencies.

4.2 GENERAL RELIABILITY/MAINTAINABILITY

Numerous engineering problems were identified during testing of the Biocube™ unit, as described in Section 3.5. Based on these observations, the Biocube™ is not yet proven as a reliable full-scale vapor treatment system.

4.3 BIOFILTRATION CONSIDERATIONS

Although biofiltration has the potential to be a cost effective treatment for TVH/BTEX vapors, large volumes of filtration media are necessary for effective treatment. Studies have shown that the longer the contact time within the biofilter medium the greater the efficiency removal for BTEX/TVH. A complete understanding of the required flow rates, influent TVH and BTEX concentrations, and necessary removal efficiencies are important when considering biofiltration as a vapor extraction treatment technology.

The use of *in situ* biofiltration will often be more cost effective than large aboveground biofilters. Recirculation of extracted soil vapors around the perimeter of a contaminated site can provide for positive control of vapors and greatly expand the soil bioreactor for remediating gasoline and other highly volatile hydrocarbons. A full-scale test of an *in situ* biofilter at Vandenberg AFB has proven very successful. Greater than 99 percent removal has been achieved with an influent of 500-1000 ppmv at a flow rate of 40 scfm (Downey, 1994). Approximately 52,000 cubic feet of soil are being utilized in this *in situ* biofilter to treat an average of 14 pounds of hydrocarbon per day. *In situ* biofiltration will be a far more cost effective method of treating lower vapor concentrations (<1000 ppmv) if the site has sufficient area to install recirculation trenches or wells.

4.4 COST

Although not a realistic alternative, the Biocube™ achieved an 18 percent removal efficiency at 49 SCFM and 1,254 ppmv influent TVH concentration with a contact time within the biofilter of approximately 1.5 minutes (90 seconds). Based on this removal efficiency, it would require approximately 12 Biocubes™ in series to achieve a 90 percent removal efficiency for TVH. Based on other vendor claims (Section 3.8), a TVH removal efficiency of $\geq$90 percent is achievable at a more realistic contact time within the biofilter medium of 6 to 20 minutes. The vendor estimated cost per kilogram of TVH removed to achieve >99% removal efficiency, using carbon treatment for polishing, ranged from $19/kg to $143/kg at concentrations of 2,000 ppmv to 250 ppmv, respectively. These costs have not been independently verified in field evaluations, and should be considered only preliminary estimates.

5.0 REFERENCES

Engineering Science, Inc. 1993. *Interim Test Results Report for Bioventing at the Patrick AFB BX Service Station.* Report provided to the Air Force Center for Environmental Excellence (AFCEE/ERT).

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